ÉCOLE DOCTORALE DES SCIENCES FONDAMENTALES

Laboratoire de Physique de Clermont

Presentation to JRJC

Title of the Thesis: 3D Volcano Imaging Using Transmission Muography

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October 18, 2021

The ANR project : DIRE (June 2020 – June 2025)

Data **I**ntegration, **R**isk and the **E**nvironment

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... with the support of INGV-Catane and the University of Geneva

Objective : Understand an active hydrothermal system to predict volcanic hazards

Vulcano (Aeolian Islands, North of Sicile) – test bench

- Active hydrothermal system, activity picks (1920, 1980)
- Population : ~5000 (< 2Km)
- Constant surveillance => other geophysical measurements will complement the muography

Muography and other imaging techniques

Wilhelm Rontgen - 1895

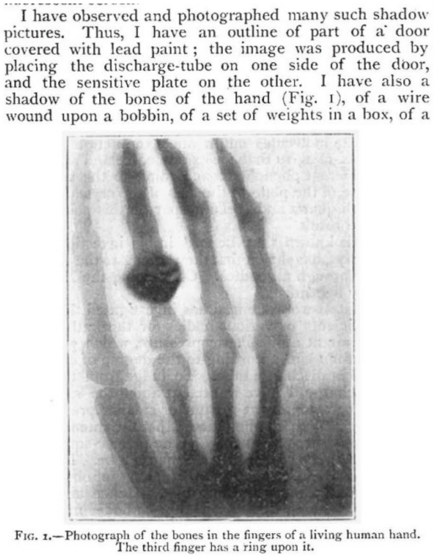
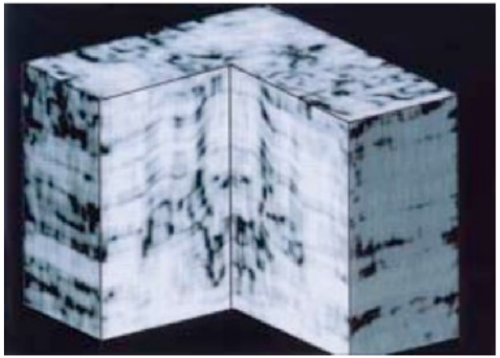
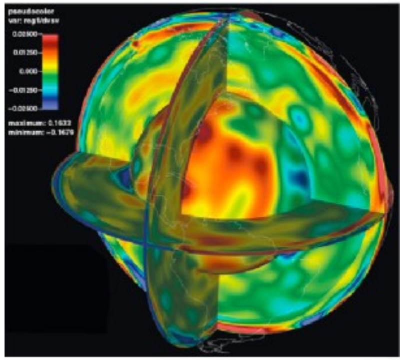

I have observed and photographed many such shadow pictures. Thus, I have an outline of part of a door covered with lead paint; the image was produced by placing the discharge-tube on one side of the door, and the sensitive plate on the other. I have also a shadow of the bones of the hand (Fig. 1), of a wire wound upon a bobbin, of a set of weights in a box, of a

FIG. 1.—Photograph of the bones in the fingers of a living human hand. The third finger has a ring upon it.

Medical

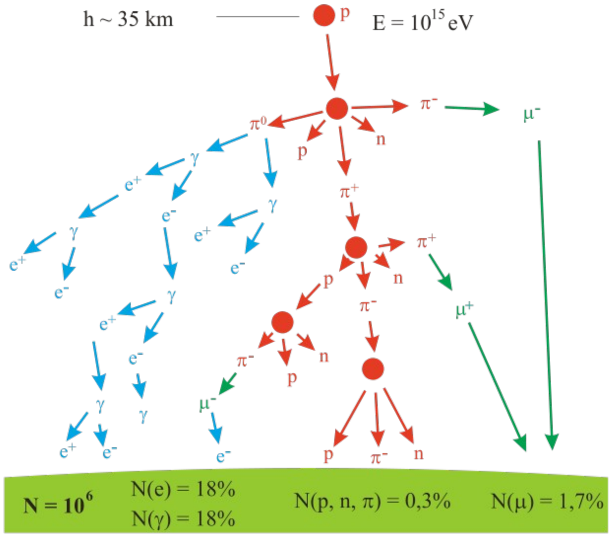
Geophysical

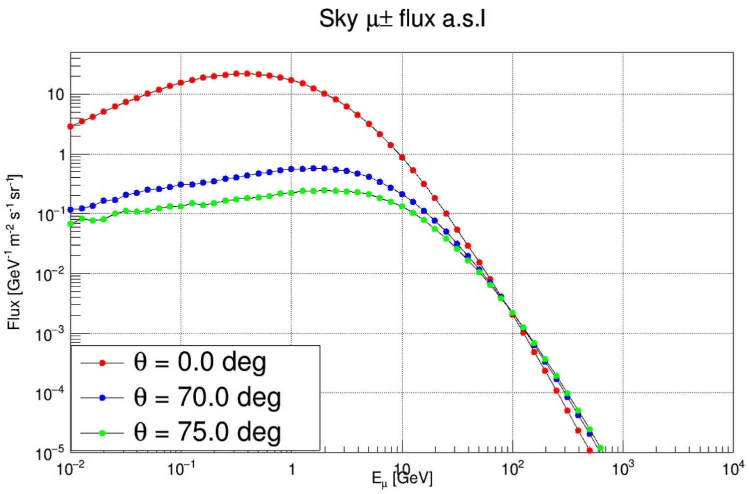




Muography

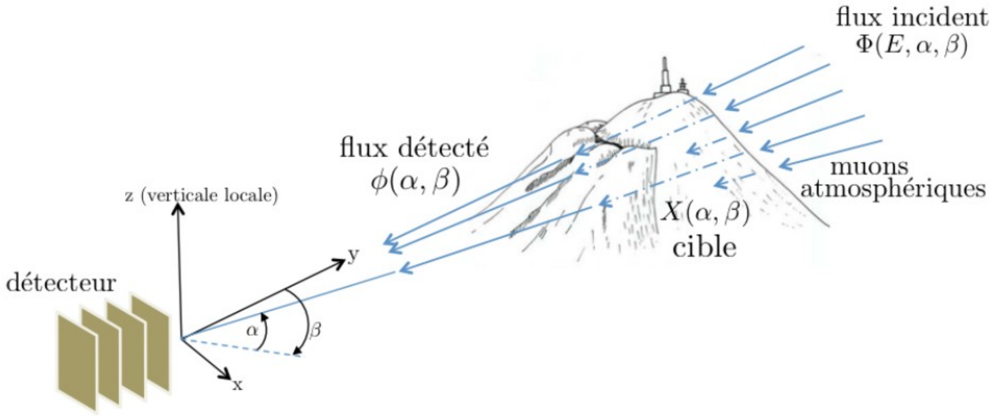
Atmospheric muon flux





At sea level: 1 muon passes through hand per second

Transmission muography technique



Need to invert $T(\alpha,\beta)=\frac{\phi(\alpha,\beta)}{\phi_0(\alpha,\beta)}$ to a density map $\rho(\alpha,\beta)$

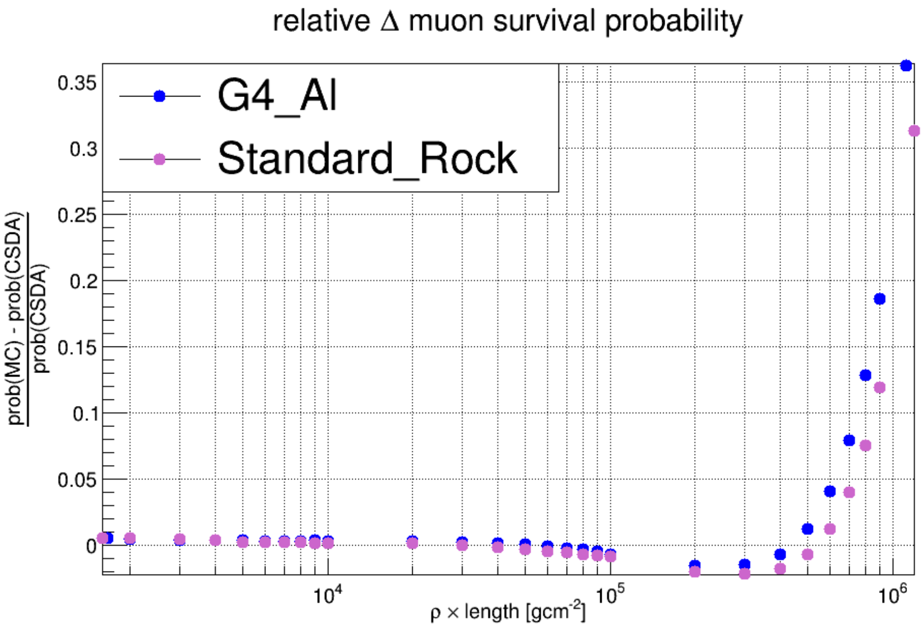
Modeling :

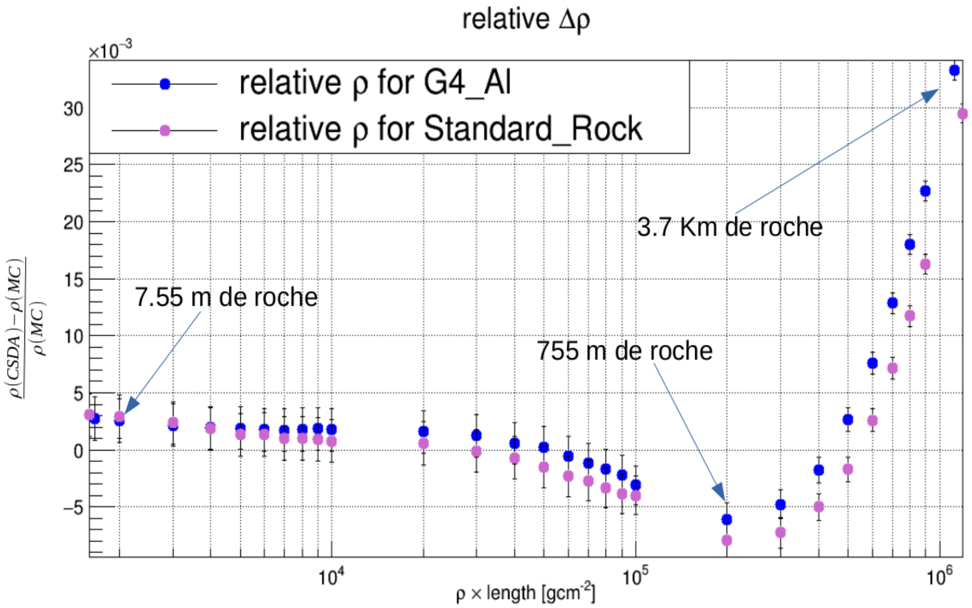
- Primary atmospheric muon flux (detailed simulation from CORSIKA)
- Target (topographic data, chemical composition, ...)
- Muon transport through the target
- Detector response

Measure === simulation(ρ, …) => $\hat{\rho}(\alpha,\beta)$ = density that best reproduces the measure

Muon transport model & survival probability

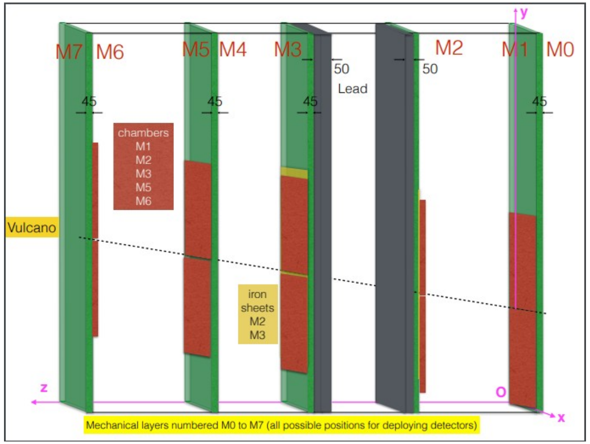
Analytical approximation : CSDA (Continuous Slow Down Approximation)
Used by many experiments
Monte Carlo treatment : MIM (Muon IMaging)





Using the CSDA approximation, thus neglecting the stochastic character of the high-energy interactions of the particles with matter, underestimates their survival probability and thus induces systematics on the reconstructed density.
In the range of kilometer of standard rock, the effect is about 3%.

MIM telescope



2 trajectographs &
10 cm of lead: (statistical) rejection of low energy muons by keeping the events where the two reconstructed tracks are well aligned

Each detection layer (1.36 x 1m2) : 4 GRPC (Glass Resistive Plate Chamber) chambers with :

- Position resolution (measured) : 1.5 mm
- Time resolution : (a few ns)
- Detection efficiency : 95%

Telescope :

- Low energy consumption, solar panels compatible (350 W)
- Data transfer & analysis on real time to LPC for a permanent surveillance of the volcano

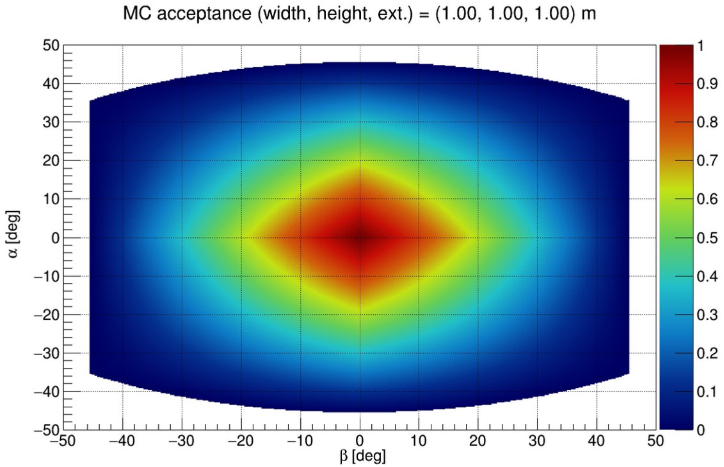
Modeling the detector response

Essentially 2 factors

- The effective surface : with data time taking give the number of reconstructed muons

$$S_{eff}(\alpha,\beta)=S_{geo}\cdot A(\alpha,\beta)\cdot\epsilon(\alpha,\beta,E_\mu)$$

S_{geo}	Geometrical surface
$A(\alpha,\beta)$	Geometrical acceptance
$\epsilon(\alpha,\beta,E_\mu)$	Detection efficiency



- The track angular resolution : repartition of reconstructed muons

Expected muon count trough Puy-de-Dôme

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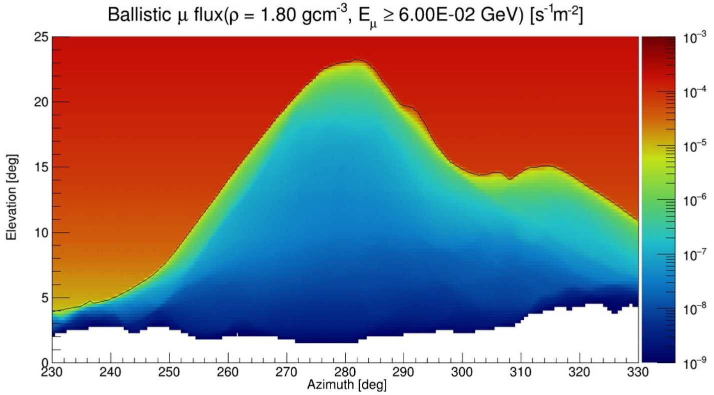
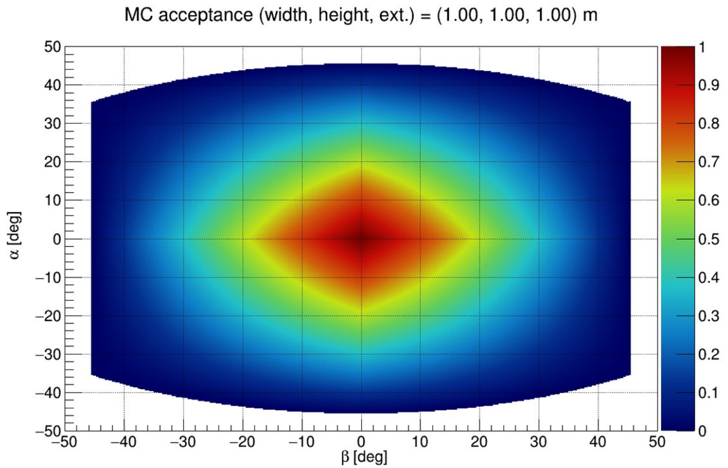
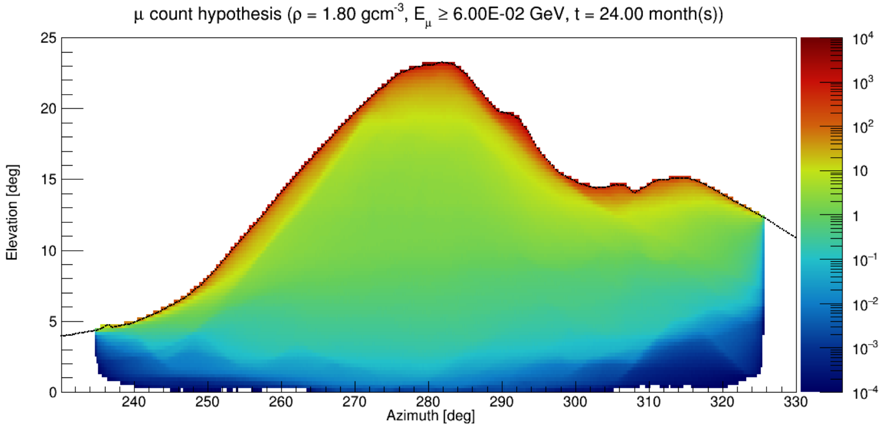


x



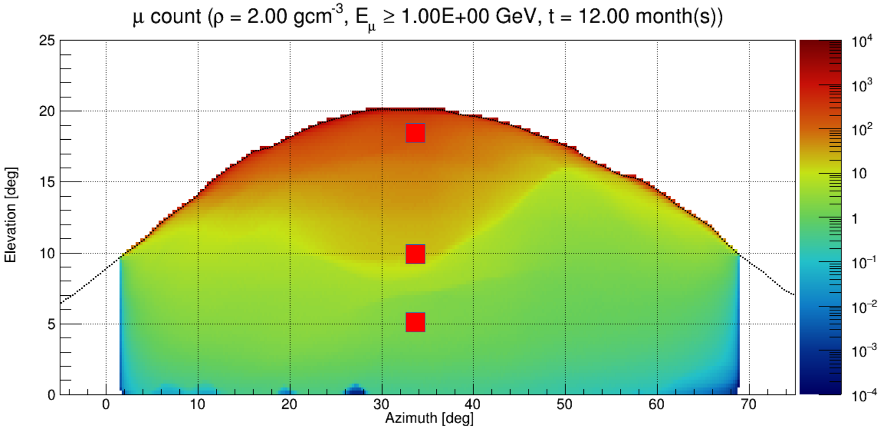
$dE_\mu \, d\Omega$

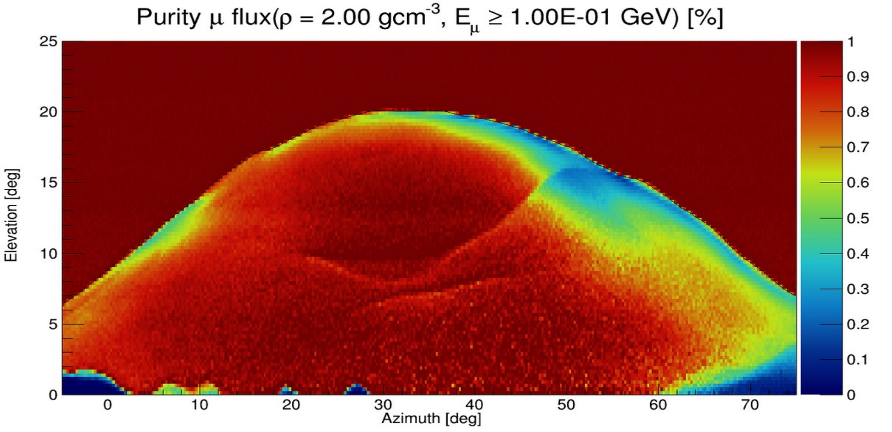


Detector site: TDF 2013
Ideal detector (efficiency = 100%) 1m^3
Duration = 2 years

N(280, 22) = 74.3 ± 0.42 muons
N(280, 15) = 2.7 ± 0.02 muons

Expected muon count trough Vulcano





N(35°, 18°) = 119.2 ± 1.13 muons
N(35°, 10°) = 19.7 ± 0.24 muons
N(35°, 5°) = 1.7 ± 0.03 muons

Ideal detector (efficiency = 100%) :

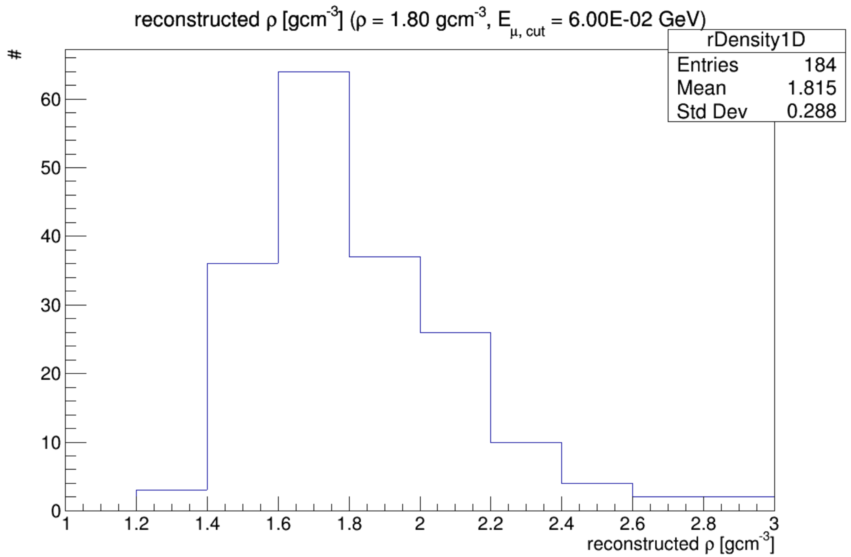
- Width: 1.4 m
- Height: 2.09 m
- Extension: 2.12 m

Duration = 1 year

Density reconstruction

Algorithm

- Initial density interval from other geophysics [ρ_{min}, ρ_{max}]
- For a direction, shrink the interval to a given width
- The density center is an estimation of the density for that direction
- Repeat to compute the mean & uncertainty



$$\rho = 1.82 \pm stat(0.3) + syst(0.05)\, gcm^{-3}$$

Conclusion

- The number of ballistic muons in a direction needed to reconstruct the density is polluted by other scattered muon arriving in that direction => need to estimate the effects on a density variation
- Measure in a direction could be not compatible to any expected muon count for a binning => need to adapt binning
- Need to optimize the algorithm for time & CPU

Predict volcanic hazards is like catching mountain oysters, as they are not happy to live in the mountains, they are aggressive

Thank you for your attention !

Back up

Hydrothermal system

A complex system involving the circulation of hot water inside the Earth's crust

- a fluid (water)
- a heat engine: thermal energy supplied by the chamber magmatic containing lava at high temperature and located a few km deep
- circulation / piping: faults and cracks generated by spacing of plates

Consequences: volume of rocks where temperature, pressure and the chemical environment is constantly changing

The water, as it infiltrates, heats up by several hundred degrees, being lighter, rises and springs to the surface at high temperature

Before volcanic eruptions, these systems record the first disturbances linked to these variations => understanding of the systems hydrothermal => prediction of volcanic hazards

Some geophysical measurements on Vulcano

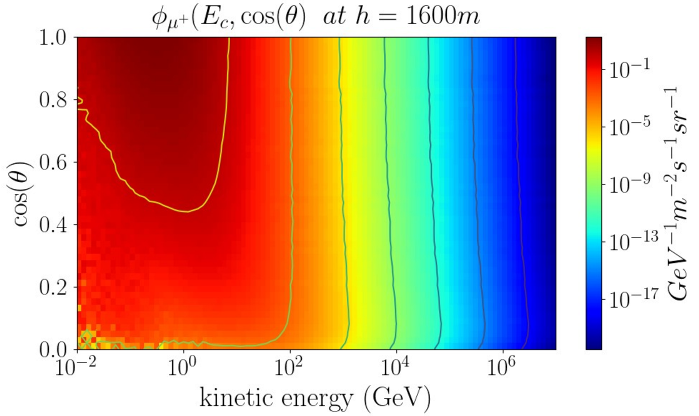
Temperature, weather (pressure & humidity) & gas

Some geophysical methods

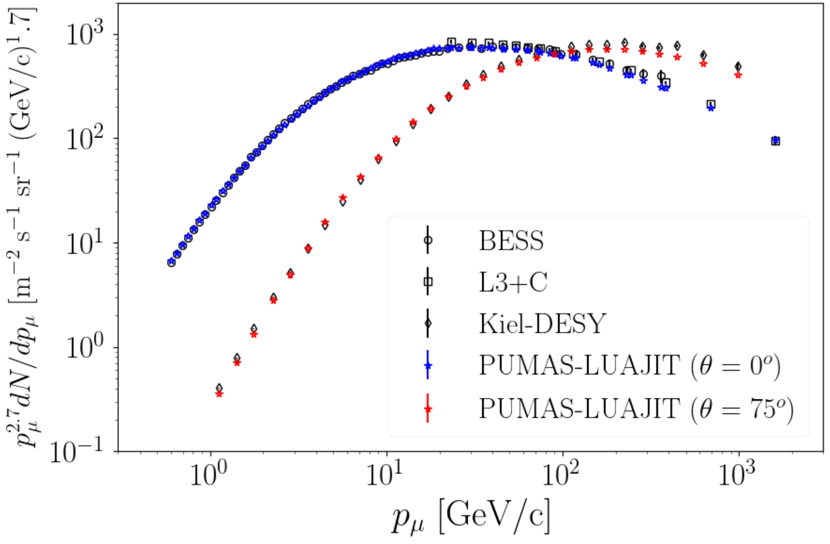
- Gravimetry (surface and subsurface density variation) - poor resolution as going deeper
- Electrical resistivity (resistivity, fluid, nature of rocks) => correlation with density
- Magnetization (local variation of the magnetic field induced by the rocks)
- Seismic tomography (elasticity and velocity of seismic waves)

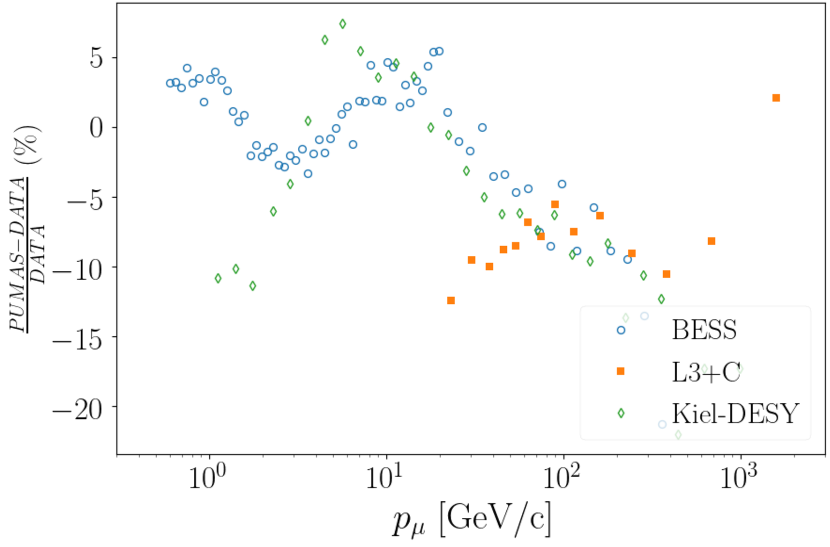
Model of the primary flux of atmospheric muons

Obtained by detailed simulation from **CORSIKA** at altitude = **1600 m**
High energy interaction: **EPOS LHC**
Low energy interaction: **FLUKA**



Muon flux a.s.l (data from arXiv :astro-ph/0403704)



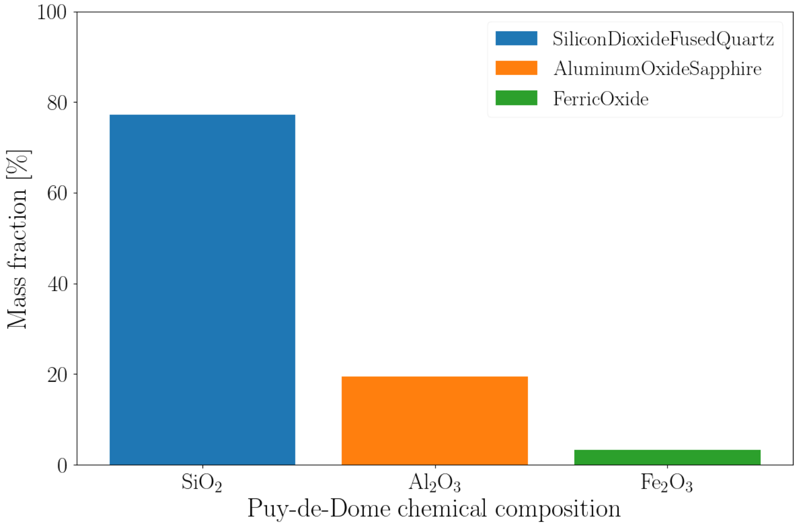


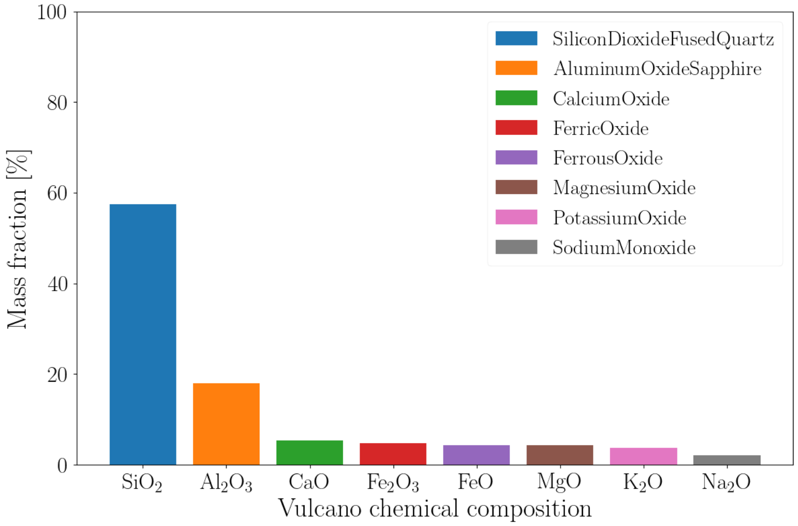
Modeling of the target (volcano)

Topography data

- **PdD** : Lidar data
  (Precision: horizontal = 0.5 m x 0.5 m, vertical = 10 cm
- **Vulcano** : fusion of data from ASTER-GDEM & GEBCO (NASA)
  (Precision: horizontal = 30 m x 30 m, vertical = 10 cm)

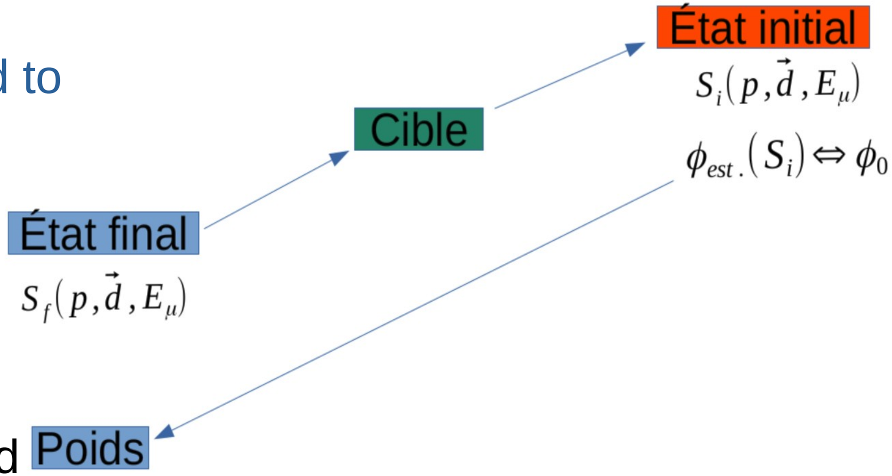
Chemical composition





Backward Monte Carlo muon transport

Initial flux estimated via final muon flux and weighted to reproduce the primary muon flux at 1600 m



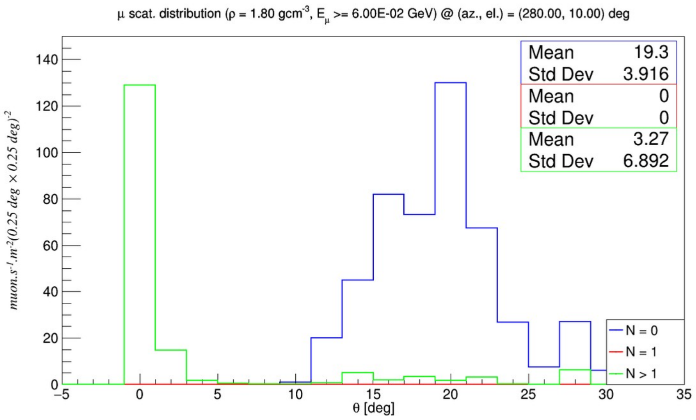
2 transport models are defined in the simulation code :

- Without scattering: particle direction in unchanged
- With scattering: particle direction change according an angle θ that follows a Gaussian dist. for θ small

These 2 transport models allow us to estimate, for a direction, the number of scattered muon that have no information on the density reconstruction

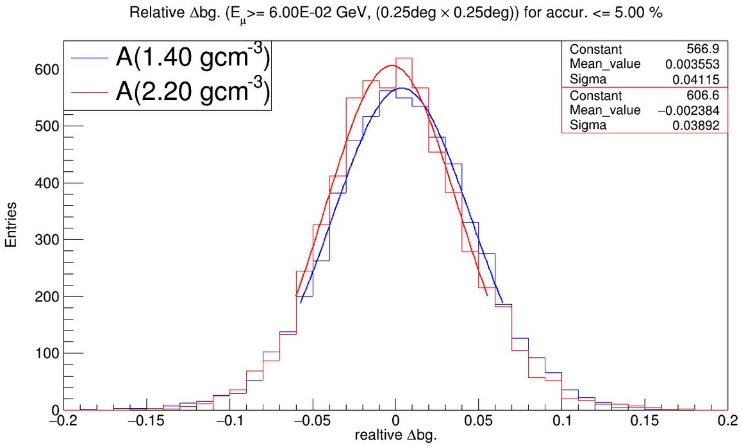
The scattering is inversely proportional with the muon momentum thus it is possible to isolate low energy muon that consider a kind of backgrounds

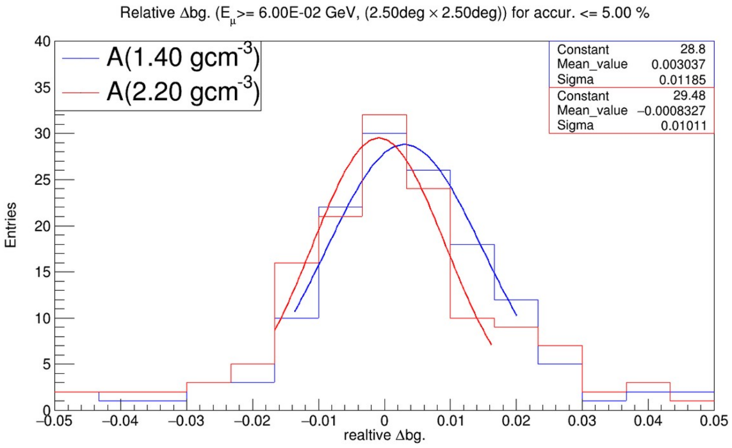
Density variation effects on backgrounds estimate



$$A(\rho)=\frac{B(\rho)-B(\rho_{ref})}{B(\rho_{ref})}$$

$$\epsilon = \sqrt{\epsilon_{B(\rho)}^2 + \epsilon_{B(\rho_{ref})}^2} \leqslant 5\%$$





A density variation of 22 % induces backgrounds variation of 0.4 % +- 4 %